network services. For example, it is possible to use cloud computing power to create such services.

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Пространственно-временная модель сигнала радиовысотомера с ЛЧМ при отражении от морской поверхности

В статье рассматриваются особенности моделирования отражённого сигнала радиовысотомера над морской поверхностью при различной высоте волн, введении углов эволюции и скорости летательного аппарата, а также изменении ширины диаграммы направленности антенны. Произведено краткое описание влияющих факторов, которые были учтены при моделировании работы радиовысотомера. Дан анализ результатов моделирования.

Space-time model of radio altimeter LFM signal reflected from the sea surface

Currently, modern computational power allows implementing quite plausible ways to simulate signals reflected from different objects. Besides the fact that modeling a random process is economically much more profitable than full-scale trials, it also allows saving time by modifying the test conditions almost instantly since all the simulation parameters are set by means of equations and constants that can be changed depending on the task. Mathematical modeling allows taking into account the features and characteristics of the radar objects under specified conditions of observation and provides the necessary accuracy of the physical processes description.

The aim of the study is the radar altimeter modeling above the sea surface.

The relevance of this topic lies in the fact that the development of low-altitude aircraft navigation systems arise the need to measure the sea state parameters in order to avoid emergencies at an altitude of up to 50 meters

The object of the study is the radio altimeter operation using a chirp signal over the sea surface.

A method of work is mathematical modeling in MatLAB that is computing environment using the phenomenological approach.

The principle of radio altimeter operation with frequency modulation is the following: a high-frequency signal with a symmetrical linear frequency modulation is radiated by the transmitting antenna and reflects from complex radar scene that consists of reflecting facets of the sea surface roughness [2, 3].

When studying sea surface it is necessary to consider the factors that influence wave generation, such as speed and wind direction, waves fetch length, ocean motion, etc. [1].

The sea state modeling algorithm is as follows [5]:

- The energy spectrum of sea waves is calculated (capillary model for ripples and TMA model for wind waves):

$$E_{TMA}(f) = E_{JONSWAP}(f) \cdot \Phi(f^*, h), \qquad (1)$$

$$E_{JONSWAP}(f) = \frac{\alpha \cdot g^2}{(2\pi)^4 \cdot f^5} e^{-\frac{5}{4} \cdot (\frac{fp}{f})^4} \cdot \gamma^{e^{-\frac{\frac{f}{fp}-1}{2 \cdot \sigma^2}}}, \qquad (2)$$

where α is the scaling parameter;

γ is the peak enhancement factor;

σ is evaluated as 0,07 for $f \le f_p$ and 0,09 otherwise;

fp is the frequency at the spectral peak;

$\Phi(f^*,h)$ is the Kitaigorodoskii depth function.

- According to this spectrum the parameters for each elementary wave of sea surface are defined (height and wavelength, direction of propagation, wave phase, etc.).
- These data, together with the aircraft speed vector, current time t and antenna direction are inserted into the analytical formula:

$$\xi(x,y,t) = \mathrm{C}\cdot\sum_{n=0}^{N_f-1}\mathrm{A}_n\sin\left(K_{0n}\cdot\left[(x+(V_x-U_{nx})\cdot t)\cdot cos\beta_n + \left(y+\left(V_y-U_{ny}\right)\cdot t\right)\cdot sin\beta_n\right]-\Omega_n\cdot t+\alpha_n\right), \quad (3)$$

where x, y is the actual location at time t;

n is the number of wave trains;

V_x,V_y is aircraft speed projection;

U_{nx}, U_{ny} is waves speed;

$x + (V_x – U_{nx})t$, $y + (V_y – U_{ny})$ is offset in the Oxy plane;

α_n is the wave phase;

β_n is the direction of wave propagation;

Ω_n is the wave pulsation;

K_{0n} is the wave number;

$N_f >> 1$ is the number of waves;

A_n is the sea wave amplitude;

C is the normalization constant.

- The resulting surface is converted into an unordered set of triangles by Delaunay triangulation (every three samples are grouped into facet) (Figure 1).
- Further, there is a calculation of each triangular facet parameters (facet area, center and normal vector).
- As a result there is a finite region of formed facets that represents sea waves.

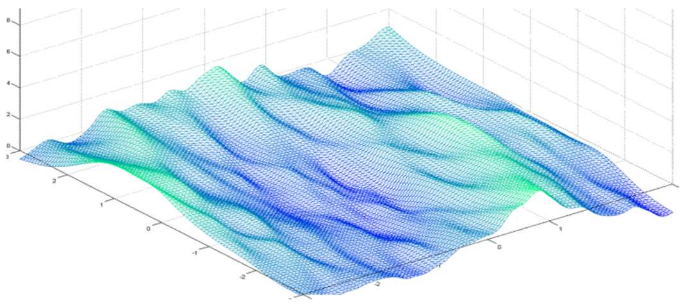


Figure 1. Discrete facets surface

Radio altimeter modeling

The underlying surface is constructed as follows: taking into account the antenna pattern it is possible to construct a conical surface with a small number of faces. Further, this surface is determined by the intersection of the horizontal plane at a suitable distance. The rectangle is constructed from the resulting set by the extreme points. It includes all facets of sea surface.

The modeling algorithm of reflected from the sea surface signal is as follows [2]:

- the scan area (area(j)) is determined by the formed sea wave facets;
- further the power of the signal reflected from each of the facets in the area (P_j), its time delay (τ_j) and Doppler frequency shift (ω_{dj}) are calculated;
- feedthrough signal (P_{ft}), its time delay (τ_{ft}) and white Gaussian noise (P_n) are measured;
- we can obtain a beat signal using previous data:

$$U_б = \sum_j \sqrt{P_j}(t) \cdot \sin\left(\frac{2\omega_д}{Tmod} \cdot \tau_j \cdot t + \omega_{дj} \cdot t + \varphi_0\right) + P_k(t) \quad (4)$$

where Tmod is signal modulation time;

φ_0 is random phase;

P_k is the sum of feedthrough and additive white Gaussian noise;

- spectrum of the beat signal is defined using fast Fourier transform FFT (Ub);
- the spectrum is assessed in three different ways: at the maximum spectral range, the leading spectral edge and the center of spectrum gravity [5].

Modeling results were obtained with different input parameters, such as:

- wind speed variation, which leads to waves speed and height change in the sea surface;
- aircraft speed, pitch and roll angles, the height above the sea level;
- antenna pattern variation.

The results are presented in Figures 2, 3, 4, 5, 6.

Each figure contains three graphs: 3-dimensional moving sea image, beat-frequency spectrum and beat-frequency signal.

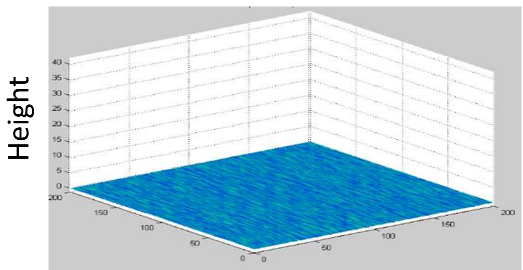
Wind speed has a direct impact on the sea surface commotion. The greater speed, the faster wave formation and as a consequence the waves become higher. Heights variation determined by altimeter becomes larger than in perfectly flat surface. The spectrum amplitude is increased because of wave heights increasing. The maximum spectral range is more uncertain due to the spread of wave heights. Figure 2 shows plots at the wind speed of 1 m/s, Figure 3 shows the plots at the wind speed of 10 m/s.

The radio altimeter antenna pattern width is one of the most important parameter. The wider it, the higher the stability of the altimeter at large angles of pitch and roll. In the model antenna pattern width is 40 degrees, which corresponds to the antenna pattern width of A-053 and A-052 altimeters [4].

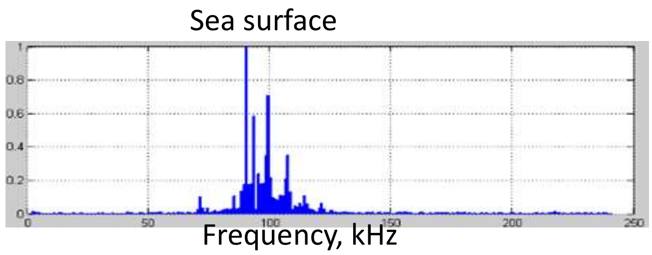
There is a slight enlargement of the spectrum in the high frequency region when increasing the beam from 40 degrees to 60 degrees. This is due to the fact that increasing of the beam width there is a consideration of the same and additional facets that are on the longer range with greater "amplitude" (Figure 4).

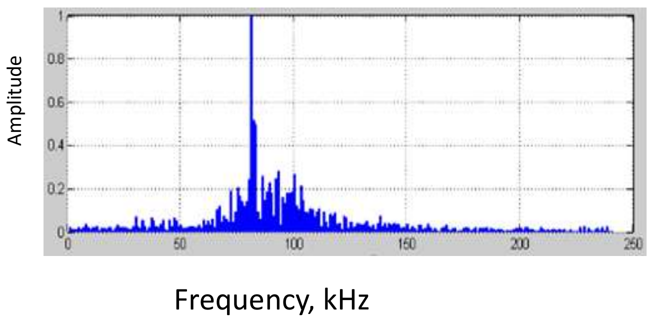
When decreasing antenna pattern, scanning area also decreases, and consequently the spectrum narrows (Figure 5).

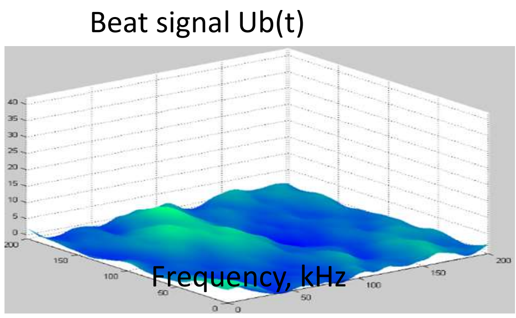
In response to a weak deviation of the antenna pattern, the spectrum shifts to higher frequencies. This is due to the fact that in case of the aircraft deviation antenna pattern will scan long-distant facets and their frequencies will appear in the spectrum. If there is a strong deviation of antenna pattern (more than half of the antenna axis), the spectral maximum shifts in the region of high frequencies. Roll and pitch are 10 degrees in Figure 6.



Beat signal spectrum. Height over the sea = 30.375 m. Spectrum width at 0.5 = 1000 Hz







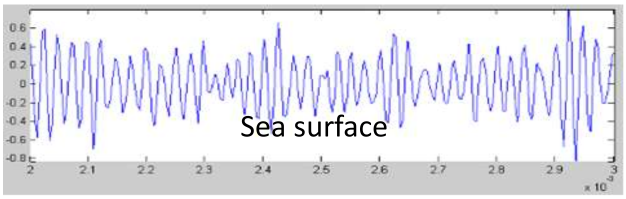


Figure 2. Output modeling data at aircraft speed = 0; height above the sea = 30 m; wind speed = 0 m/s; no pitch and roll angles; antenna pattern width = 40^0

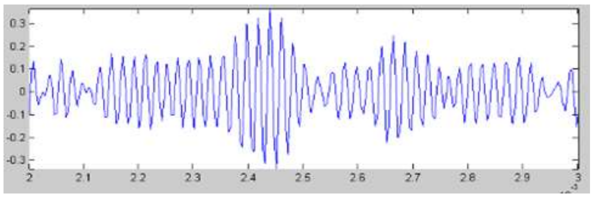
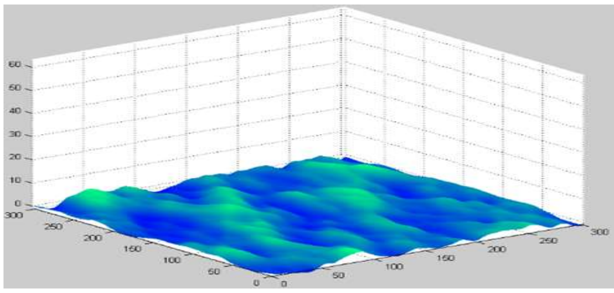
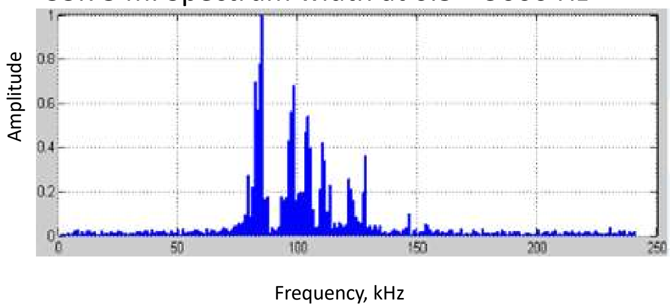


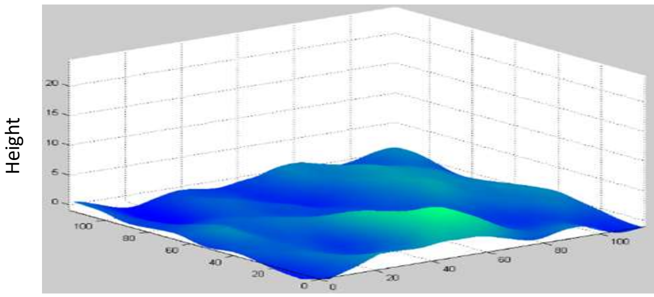
Figure 3. Output modeling data at aircraft speed = 0; height above the sea = 30 m; wind speed = 10 m/s; no pitch and roll angles; antenna pattern width = 40^0



Beat signal spectrum. Height over the sea = 30.75 m. Spectrum width at 0.5 = 22000 Hz

Beat signal spectrum. Height over the sea = 33.75 m. Spectrum width at 0.5 = 9000 Hz





Beat signal spectrum. Height over the sea = 30.75 m. Spectrum width at 0.5 = 11000 Hz

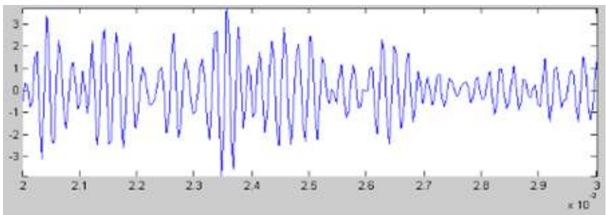
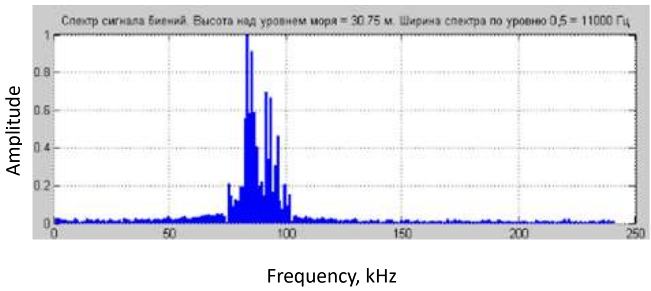
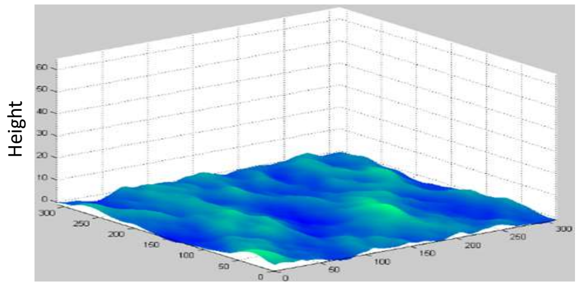


Figure 4. Output modeling data at aircraft speed = 0; height above the sea = 30 m; wind speed = 10 m/s; no pitch and roll angles; antenna pattern width = 60^0





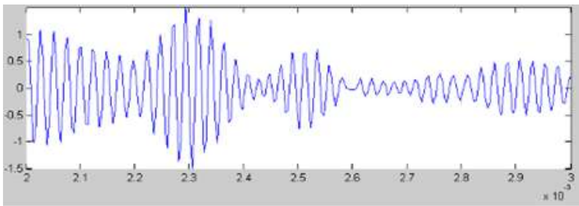
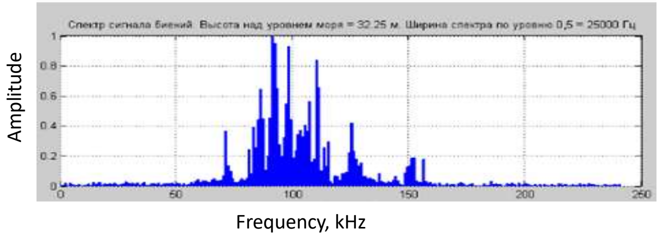


Figure 5. Output modeling data at aircraft speed = 0; height above the sea = 30 m; wind speed = 10 m/s; no pitch and roll angles; antenna pattern width = 20^0



Beat signal spectrum. Height over the sea = 32.25 m. Spectrum width at 0.5 = 25000 Hz

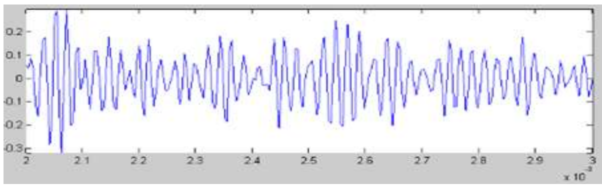


Figure 6. Output modeling data at aircraft speed = 0; height above the sea = 30 m; wind speed = 10 m/s; pitch and roll angles = 10^0; antenna pattern width = 40^0

We can determine the errors for each of the following spectrum estimates when calculating the heights above sea level.

Figures 7 and 8 show the height measurement estimation errors above the sea in the absence disturbances at the sea surface and in the presence of waves up to 4 meters high (wind speed is 10 m/s). The measurements are performed at attitudes up to 50 meters and typical conditions for radio altimeters operation [3].

Relative measurement error is defined by the following formula [1]:

$$\delta_{\mathrm{x}} = \Delta\mathrm{x}/\mathrm{X}_{true}\ , \qquad (5)$$

where δ_{x} is relative measurement error; $\Delta\mathrm{x} = |\mathrm{X}_{true} - \mathrm{X}_{meas}|$ is absolute error; $\mathrm{X}_{\mathrm{true}}$ is true value and $\mathrm{X}_{\mathrm{meas}}$ is measured value.

The results are obtained using the known measuring methods [3] (the maximum spectral range, the leading spectral edge and the center of spectrum gravity) in two states of the sea surface.

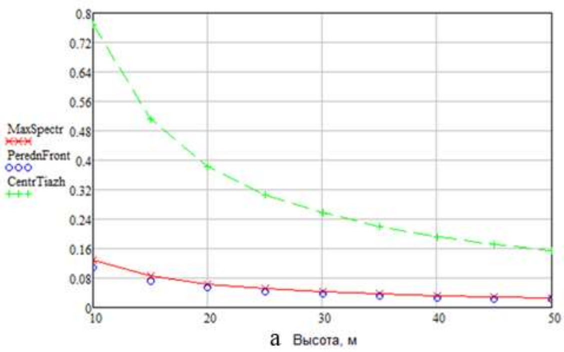


Figure 7. The relative error of the aircraft height determination that depends on the height of the flight in zero wind speed: MaxSpectr is the maximum range spectrum estimate; PerednFront is the leading spectrum edge estimate; CentrTiazh is the center of spectrum gravity estimate

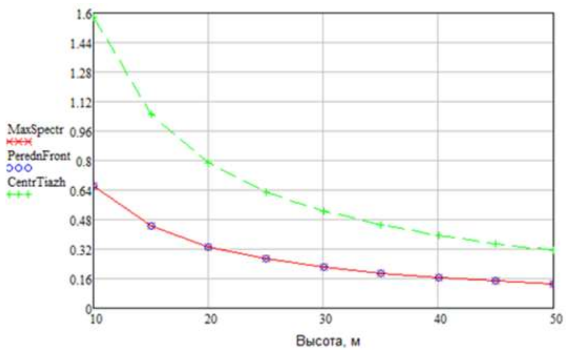


Figure 8. The relative error of the aircraft height determination that depends on the height of the flight in 10 m/s wind speed: MaxSpectr is the maximum range spectrum estimate; PerednFront is the leading spectrum edge estimate; CentrTiazh is the center of spectrum gravity estimate

As we can see from the figures above the center of spectrum gravity has the greatest error. The leading spectrum edge estimate is the most accurate.

As the work result, mathematical model considering the sea surface parameters impact on the beat signal and accuracy of altimeter work is developed. It allows exploring the faceted surface. The sea waves dynamics is implemented at different wind speeds. The analysis of the modeling results is made.

The developed model adequacy is analyzed by changing the following input parameters: flight height variation above sea surface, the addition of the aircraft pitch and roll angles, establishment of the wind and aircraft speeds and changing the width of the antenna pattern.

As it can be seen from the results, the radio altimeter mathematical model is adequate enough and corresponds to the field experiments data [3].

Applications include aircraft radar navigation systems. This work provides the opportunity to carry out mathematical and HIL modeling of radio altimeter systems under various external influences without expensive field tests.

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Обзор технологии «Дополненная реальность»

В статье рассматривается технология дополненной реальности, описаны принципы работы, компоненты для реализации, сравнение данной технологии с виртуальной реальностью. Рассмотрены существующие реализации приложений на основе дополненной реальности. Предоставлена информация о перспективах развития технологии.